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PARAMETRIC STUDY OF COMPONENT SELECTION AND OPERATION ON GENERIC DRAIN-BACK SOLAR WATER HEATER CERTIFICATION

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ABSTRACT

Early experimental results of a research program to investigate the practicality of replacing the Solar Rating and Certification Corporation four day rating procedure with a more cost effective rating method for generic solar domestic hot water systems are reported. The generic systems experimental procedure and facility are described. Results from four experiments give an initial indication that the recirculation flow rate has little effect on system rating. Further experiments are required to assess the feasibility of replacing the current rating method with a simulated rating.

1. INTRODUCTION

Certification of solar domestic hot water systems (DHW) by the Solar Rating and Certification Corporation (SRCC) currently requires an expensive four day test (1) which must be repeated if component or operating modifications are made. This procedure places a significant economic burden on a low sales volume industry and reduces the overall cost competitiveness of solar DHW versus conventional DHW systems. A research program supported by the Department of Energy to investigate the feasibility of a more cost effective rating method is in progress at the Solar Energy Applications Laboratory (SEAL) in conjunction with the University of Wisconsin and SRCC. The primary objective of the research is to determine if TRNSYS (2) can be used to accurately predict system ratings over a wide range of component and operating modifications. A second objective is to provide an energy rating label similar to those used by the Federal Trade Commission (3) for electric and gas water heaters. The three generic solar DHW systems included in the study are: drain-back, recirculation, and anti-freeze.

System performance is investigated using a statistical design of experiments methodology (4). This approach minimizes experiments required to determine all significant effects. A half-factorial experiment is used to characterize the effects of collector flow rate, recirculation flow rate, collector area, solar storage tank volume, and solar storage tank design on performance. This paper presents both the experimental procedure developed at SEAL in support of the program and preliminary results of the effects of collector area, collector loop flow rate and recirculation flow rate on drain-back system rating. Energy quantities determined for four SRCC rating tests are reported.

2. METHODOLOGY

2.1 Overview of SRCC Rating Procedure

The SRCC rating method consists of a four-day test in which the system environment and operational parameters are specified. Specified rating conditions are listed in Table 1. System performance is determined by monitoring temperatures, flow rates, energy usage, and energy delivery throughout the system. Rating is based on daily energy quantities measured on the last day of testing when convergence occurs. Rating is specified by the average of the last two days when convergence does not occur. Total daily energy quantities are sketched in Fig. 1. Energy delivered by the solar collector(s) is Q_u. Energy drawn from the solar storage tank relative to water main temperature, Q_s, minus the parasitic energy used by controllers and pumps, Q_{par}, is Q_{net}. Daily energy input into the auxiliary hot water heater is Q_{aux}. Reserve energy left in the solar storage tank at the end of the test is Q_{res}. Capacity of the system, Q_{cap}, is the amount of energy the system can deliver relative to water main temperature without solar input. The expressions used to determine these energy quantities from experimental data are given in the Appendix.

Solar radiation input is simulated with an electric in-line heater located downstream of the collector array which is situated in a constant temperature dark room. The in-line heater input is controlled according to the SRCC specified hourly solar profile (5) and calculations outlined in an American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) standard (6). Collector characteristics determined in a separate collector rating procedure (7) must be provided prior to rating.

Daily hot water load is based on energy and is made in three equal draws at 8:00am, 12:00pm, and 5:00pm. The SRCC draw energy is currently specified as 14.1 MJ, but is increased in current testing to 16.6 MJ to comply with the load

TABLE 1. SRCC RATING CONDITIONS

Condition	Value	Notes
I_T	17.03 MJ/m^2	An hourly profile is specified.
m_4	0.2 kg/s	
Q_{dl}	42.3 MJ	The daily load is divided among 3 equal draws at 8:00, 12:00 and 17:00. This value is revised to 49.8 MJ in the generic systems experiments.
T_a	22 ±2 C	
T_{main}	22 ±1 C	
T_{pre}	≤ 45 C	
T_{set}	≥ 48.9 C	

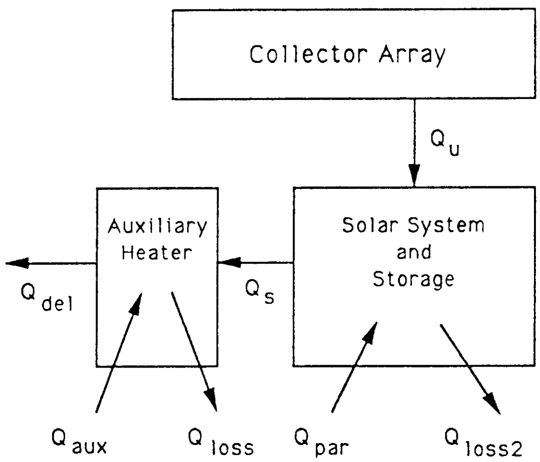

Fig. 1. System energy transfer.

specified by the Federal Trade Commission for conventional water heaters.

The test is completed at the end of four days or when the daily value of Q_{aux} is within 3 percent of the previous day's value, which ever comes first. At the end of the test, a continuous draw is made on the solar storage tank to determine the reserve capacity. The draw is continued until the outlet temperature of the storage tank is within 3°C of the inlet temperature.

2.2 Drain-Back System

The generic drain-back system as installed in the laboratory is shown in Fig. 2. The conditioned collector space is in an area between the inner roof and outer false roof of Solar House II at SEAL. The majority of the components are located in the basement of the house. Unless indicated, component descriptions listed in Table 2 are those provided by the manufacturer. Figure 3 is a schematic of the instrumented system with measurement points indicated. Data acquisition and control functions are automated for the complete test procedure. Instrumentation specifications, including system control and data acquisition hardware, are listed in Table 3. Transducers are calibrated in place with the data acquisition system.

The temperature of the collector space is maintained with a window type air conditioner and an electric space heater. Both heater and air

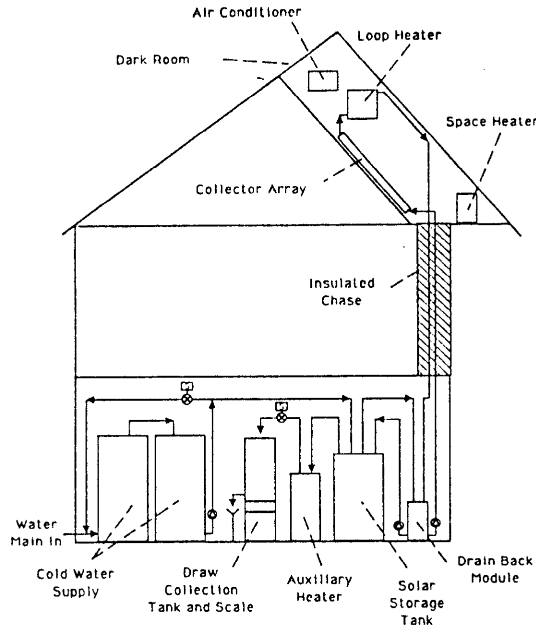

Fig. 2. Drain-back system installed in laboratory.

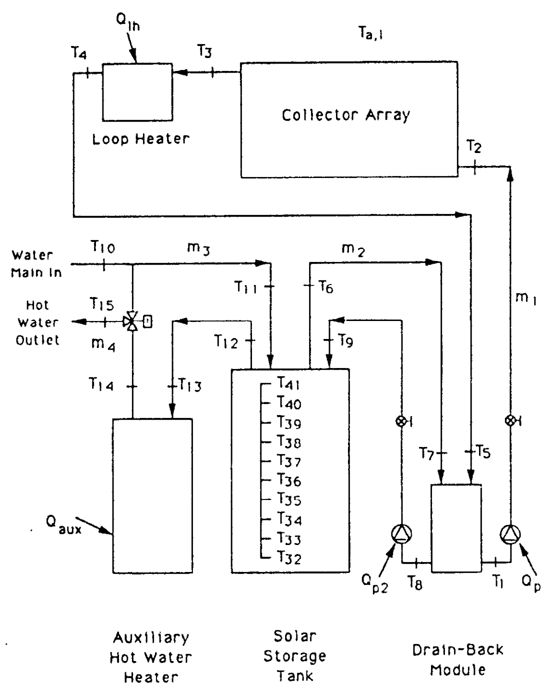

Fig. 3. Schematic of drain-back system indicating measurement points.

conditioner are independently controlled to maintain temperature within specification. The inner walls of the collector room are insulated and lined with black mylar. The collector loop heater is an in-line hot water heater with four separately controlled heating elements. The loop heater output is regulated by staging the four heating elements and varying the input voltage using a motor controlled rheostat. The use of the by-pass loop suggested in the ASHRAE 95 standard is not possible with the drain-back system because the collectors remain dry after draining until the system pumps are turned on.

The system controller supplied by the manufacturer cannot be used since the collector array is not irradiated. The behavior of a dead-band type solar controller is emulated through appropriate algorithms in the control software.

The cold water supply consists of two 300 l DHW tanks. The tanks are piped in series and a recirculation pump is used to mix the water in the tanks. The temperature of the cold water supply is measured with a thermocouple tree located in one of the tanks and a thermocouple in the outlet of the other. The tank heating elements are computer controlled to maintain the temperature within SRCC specifications. The hot water drawn empties into a plastic barrel which is mounted on top of a beam balance scale. The scale is only used for calibration of the flowmeters. During a four day rating, the barrel is allowed to drain continually.

Data acquisition/analysis and system control are integrated using a single personal computer. Details of control and data acquisition are reported by Carlson et al. (8) All transducer outputs are sampled 10 times per second. A running average of the ten most recent samples is kept and used when reporting data to file. Data is written to file at varying rates during the test. During a hot water draw, data is recorded every 15 seconds. Data is recorded every 15 minutes during simulated daylight hours. Data is recorded every 30 minutes during overnight periods.

TABLE 2. SYSTEM COMPONENT SPECIFICATIONS

COMPONENT	SPECIFICATION	VALUE
Collector	Area (large)	5.56 m^2
	(small)	2.78 m^2
	$F_R \tau\alpha$	0.60
	$F_R U_L$	5.55 W/m^2C
	$K_{\tau\alpha}$	$1 - 0.45[(1/\cos\theta) - 1]$
Solar storage tanks:		
Large	Volume	310 l
	UA	4.27 W/C *
	R-value	2.10 C m^2/W
Small	Volume	250 l
	UA	Unknown
	R-Value	2.10 C m^2/W
Auxiliary DHW	Volume	159 l
	UA	2.18 W/C *
	R value	2.19 C m^2/W
Drain-back module	Volume	30 l *
	Effectiveness	0.6 *
	UA	Unknown
Pumps:		
Collector	Type	Centrifugal Cartridge
		Power (nominal)137 W *
Recirculation	Type	Centrifugal Cartridge
		Power (nominal)67 W *
Piping	Size and Type	Type L Copper, 1.9 cm
	Insulation Type	Closed Cell Foam, 1.9 cm
	Insulation R-value	0.82 C m^2/W
	<u>Lengths:</u>	
	Drain Back Module to Collector	11.17 m*
	Collector to Loop Heater	1.39 m*
	Loop Heater to Drain-back Module	12.55 m*
	Drain Back Module to Solar Storage Tank	2.25 m*
	Solar Storage Tank to Drain Back Module	2.27 m*
Valves	Type	Gate
	Size	19 mm

* indicates measured value

2.3 Design of Experiments

The two-level, half-factorial experiment is structured with the aid of a computer package (9). The drain-back experiment uses five factors: (A) collector flow rate, (B) recirculation flow rate, (C) collector area, (D) solar storage tank volume, and (E) solar storage tank design. The tank design factor involves a diffuser to improve tank stratification.

The values selected for the two levels of each factor are based on current industry standards. They represent a baseline value at one end and a modified value at the other. Design and operational modifications are restricted to those for which system response is linear in the variables and their interactions. Radical system modifications, such as micro-flow, which might require a non-linear representation are not considered. The high and low values for each

TABLE 3. INSTRUMENTATION

Measurement	Transducer Description	Range	Accuracy	Notes
T	T-type thermocouple (special limits)	0 to 100C	±0.4%	
Delta T	T-type thermopile, 5 junction (special limits)	0 to 100C	±(1%R+0.05C)	
m_1	EG&G Flow Technologies, Inc. Turbine type Model FT-12NEXW-LED-1. Pulse Rate Converter Model RC51-1-C-1000-6	0.057 to 0.114 l/s	±0.5% linearity Std Err=.0016 l/s	1,3
m_2	EG&G Flow Technologies, Inc. Turbine type Model FT-12NEXW-LED-1. Pulse Rate Converter Model RC51-1-C-1000-6	0.047 to 0.095 l/s	±0.5% linearity Std Err=.0011 l/s	1,3
m_3	EG&G Flow Technologies, Inc. Turbine type Model FT-12NEXW-LED-1. Pulse Rate Converter Model RC51-1-C-1000-6	0.2 l/s nominal	±0.5% linearity Std Err=.1646 kg	1,2,3
m_4	EG&G Flow Technologies, Inc. Turbine type Model FT-12NEXS-LAD-2. Pulse Rate Converter Model RC51-3-A-0000-6	0.2 l/s nominal	±0.5% linearity Std Err=.1927 kg	1,2,3
Q_{in}	Ohio Semitronics Watt Transducer Model PC5-59CX5	220 to 4000 W	Std Err=5.62 W	1,4
Q_{aux}	Ohio Semitronics Watt Transducer	3000 W		4
Q_{p1}	F.W. Bell Watt Transducer Model PX2204B	137 W nominal	Std Err=1.11 W	1,4
Q_{p2}	F.W. Bell Watt Transducer Model PX2204B	67 W nominal	Std Err=0.12 W	1,4

Data Acquisition and Control Unit Hardware		Specifications
Computer	AT&T Model 6386 WGS	Intel 80386, 20 MHz, 80387 co-processor
D/A board	Metrabyte DAS-16	12 bit, 100 kHz, 8 differential inputs
Input amplifiers and multiplexers	Metrabyte EXP-16	16 differential inputs, cold junction compensation
Digital output	Metrabyte PIO-12	24 TTL digital I/O lines
Relay board	Metrabyte ERB-24	24 DPDT relays, 3 amp

Notes:
1. Standard error is based on error of calibration measurements from linear curve fit.
2. Flowmeters 3 and 4 are calibrated on the basis of mass delivered.
3. Mass flow rate is calculated from the volumetric flow rate measurement using a density factor which is a function of temperature at the flowmeter.
4. Daily energy is calculated from the power measurement by integrating over time.

factor are given in Table 4. The factor combinations which make up the initial sixteen SRCC rating experiments are listed in Table 5.

The results of the SRCC rating experiments include daily energy values: Q_s, Q_{net}, Q_{res}, and Q_{par}. Each of these values, as well as the discrepancy between experiment and TRNSYS simulation, is considered a response, y. The change in a response caused by a change in the level, L, of a particular factor, or combination of factors, is defined as the effect on that response. The average effect is calculated by summing the response value from all experiments using the +1 and -1 designations for the factor levels as coefficients and dividing by n/2 where n is the number of experiments. This is shown in Eqn. 1 for factor A by letting y_i represent a response from experiment i, L_{Ai} represent the factor level +1 or -1, and M(A) the effect of A on response y. The average value of a response from all experiments is designated as R.

$$M(A) = \sum_{i=1}^{n} \frac{L_{Ai} Y_i}{\frac{n}{2}} \quad . \tag{1}$$

TABLE 4. HIGH/LOW VALUES FOR EACH FACTOR

FACTOR DESCRIPTION	HIGH VALUE	LOW VALUE
A - Collector Flow Rate	0.114 l/s	0.057 l/s
B - Recirculation Flow Rate	0.095 l/s	0.047 l/s
C - Collector Area	5.56 m^2	2.78 m^2
D - Solar Storage Tank Volume	310 l	250 l
E - Solar Storage Tank Design	Basic	Diffuser

Effects are calculated for each factor (A, B, C, D, E) and each factor interaction (AB, BC, CD, DE, AE, ABC, etc.). A linear model of the response as a function of the factor levels is then created by summing the factor and factor interaction levels (-1 to +1) using one half the value of the associated effects as coefficients. The model is expressed as,

$$y = R + \frac{M(A)L_A + M(B)L_B + \ldots + M(AB)L_{AB} + \ldots}{2} \quad . \tag{2}$$

The statistical significance of each effect on the response is then assessed and retained. The effects that are retained are those for which the difference between the experimental and TRNSYS results are significant when a factor, or combination of factors, is changed.

In a half-factorial design, effects are confounded when two effects can not be distinguished. The confounding structure in this case is AB = CDE, AC = BDE, AD = BCE, AE = BCD, BC = ADE, BD = ACE, BE = ABD, CD = ABE, CE = ABD, and DE = ABC. The equality AB = CDE means, for example, that in comparing the TRNSYS simulation and experimental data, the result of changing collector and recirculation flow rates, M(AB), can not be differentiated from the result of modifying collector area, tank volume and tank design, M(CDE). If a significant effect is confounded, additional experiments are required to distinguish between the two confounded effects.

3. RESULTS

Four experimental trials have been completed. The results of these experiments are listed in Table 6. The completed experiments form a two-level, half-factorial experimental design involving the three factors: collector flow rate, recirculation flow rate, and collector area. This subset of the generic systems experimental design is represented graphically in Fig. 4 by factor combinations 10, 11, 13, 16. The axes of the cube represent the factors: (A) collector flow rate, (B) recirculation flow rate, and (C) collector area. The +1 and -1 designations represent the high and low levels for each factor. The effects representation table for this experimental subset is given in Table 7.

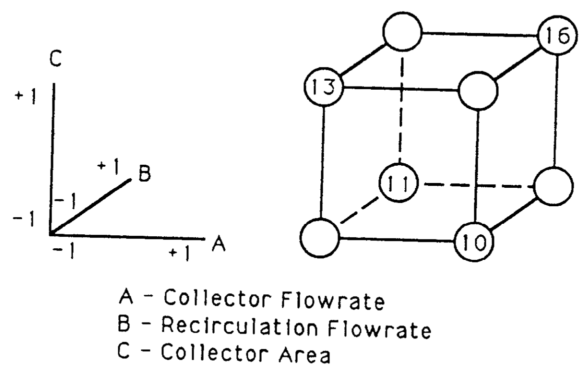

Fig. 4. Graphical representation of two-level factorial experimental design.

TABLE 5. FACTOR COMBINATIONS FOR INITIAL TRIALS OF GENERIC SYSTEMS PROGRAM

Factor Combination	Collector Flow Rate (l/s)	Recirculation Flow Rate (l/s)	Collector Area (m^2)	Solar Storage Tank Volume (l)	Solar Storage Tank Design
1	0.057	0.047	2.78	250	Basic
2	0.114	0.047	2.78	250	Diffuser
3	0.057	0.095	2.78	250	Diffuser
4	0.114	0.095	2.78	250	Basic
5	0.057	0.047	2.78	250	Diffuser
6	0.114	0.047	2.78	250	Basic
7	0.057	0.095	2.78	250	Basic
8	0.114	0.095	2.78	250	Diffuser
9	0.057	0.047	5.56	310	Diffuser
10	0.114	0.047	5.56	310	Basic
11	0.057	0.095	5.56	310	Basic
12	0.114	0.095	5.56	310	Diffuser
13	0.057	0.047	5.56	310	Basic
14	0.114	0.047	5.56	310	Diffuser
15	0.057	0.095	5.56	310	Diffuser
16	0.114	0.095	5.56	310	Basic

TABLE 6. GENERIC SYSTEMS EXPERIMENTAL RESULTS SUMMARY

FACTORS					EXPERIMENTAL RESULTS							
Col. Flow (l/s)	Recirc. Flow (l/s)	Col. Area (m^2)	Tank Volume (l)	Tank Design	SF (%)	Qs (kJ)	Qnet (kJ)	Qres (kJ)	Qaux (kJ)	Qpar (kJ)	Qp1 (kJ)	Qp2 (kJ)
.057	.047	2.78	250	Basic								
.114	.047	2.78	250	Diffuser								
.057	.095	2.78	250	Diffuser								
.114	.095	2.78	250	Basic								
.057	.047	5.56	250	Diffuser								
.114	.047	5.56	250	Basic								
.057	.095	5.56	250	Basic								
.114	.095	5.56	250	Diffuser								
.057	.047	2.78	310	Diffuser								
.114	.047	2.78	310	Basic	19.0	14864	9442	11966	41120	5422	3491	1931
.057	.095	2.78	310	Basic	15.7	13212	7790	11840	42626	5422	3444	1978
.114	.095	2.78	310	Diffuser								
.057	.047	5.56	310	Basic	32.6	21628	16247	17942	34671	5381	3423	1958
.114	.047	5.56	310	Diffuser								
.057	.095	5.56	310	Diffuser								
.114	.095	5.56	310	Basic	37.9	24338	18882	24390	31781	5455	3516	1939

TABLE 7. EFFECTS REPRESENTATION TABLE OF SUBSET OF EXPERIMENT DESIGN

Factor Combination	Factors A	B	C	Interactions AB	BC	AC	ABC	Response
10	1	-1	-1	-1	1	-1	1	y10
11	-1	1	-1	-1	-1	1	1	y11
13	-1	-1	1	1	-1	-1	1	y13
16	1	1	1	1	1	1	1	y16

The average effects due to factor A (collector flow rate), factor B (recirculation flow rate), factor C (collector area), and possible factor interactions are expressed as,

$$M(A) = \frac{+Y_{10} - Y_{11} - Y_{13} + Y_{16}}{2} , \tag{3a}$$

$$M(B) = \frac{-Y_{10} + Y_{11} - Y_{13} + Y_{16}}{2} , \tag{3b}$$

$$M(C) = \frac{-Y_{10} - Y_{11} + Y_{13} + Y_{16}}{2} , \tag{3c}$$

$$M(AB) = \frac{-Y_{10} - Y_{11} + Y_{13} + Y_{16}}{2} , \tag{3d}$$

$$M(BC) = \frac{+Y_{10} - Y_{11} - Y_{13} + Y_{16}}{2} , \tag{3e}$$

$$M(AC) = \frac{-Y_{10} + Y_{11} - Y_{13} + Y_{16}}{2} , \tag{3f}$$

$$M(ABC) = \frac{+Y_{10} + Y_{11} + Y_{13} + Y_{16}}{2} . \tag{3g}$$

The confounding in this case is demonstrated by M(A) = M(BC), M(B) = M(AC), and M(C) = M(AB). The effects based on responses Qnet and Qs are presented in Table 8 in order of magnitude.

TABLE 8. EFFECTS ANALYSIS BASED ON RESPONSES Q_{net} AND Q_s

Effect	Q_{net} Response	Q_s Response
R	13090 kJ	18511 kJ
M(C) = M(AB)	8949 kJ	8945 kJ
M(A) = M(BC)	2144 kJ	2181 kJ
M(B) = M(AC)	492 kJ	529 kJ

The results in Table 8 indicate that recirculation flow rate (B), has much smaller effects on Q_{net} and Q_s than do collector flow rate (A) and collector area (C). However, the interaction of recirculation flow rate with collector flow rate (A) and collector area (C) may be significant. Additional experiments beyond the remaining twelve may be required to resolve the confounding. Confounding resolutions will be based on finding significant differences between experimental results and TRNSYS predictions.

The response Q_{net} was chosen for the analysis of this paper because it is considered the most important value of the SRCC rating test. It indicates what is gained by installing the solar DHW system. The response Q_s was chosen due to the large amount of energy that is consumed by pumps in the experiment. The parasitic energy, Q_{par}, represents between 22 and 41 percent of the delivered energy, Q_s, for the four experiments. In the analysis of Q_s, the pump power is excluded, but the relative magnitude of the effects are nearly the same.

A model can be constructed for Q_{net} based on the four experiments by assuming the effects are due to the individual factors only and that no interaction effects exist.

$$Q_{net} = I + \frac{M(A)\,L + M(B)\,L_B + M(C)\,L_C}{2} . \tag{4}$$

Substituting the values from Table 8,

$$Q_{net} = 13090 + 1072\,L_A + 246\,L_B + 4475\,L_C \text{ kJ} . \tag{5}$$

This model fits the data exactly since only four data points exist. Statistical data analysis will be determined when further experiments are completed. If the effect due to B is removed from the model then the standard error between the model and the data is 246 kJ. This corresponds to an error of 3.2 percent at a Q_{net} of 7790 kJ.

4. CONCLUSION

An experimental program has been initiated whose purpose is to confirm whether TRNSYS can accurately predict the SRCC ratings for a solar DHW system as defined by the generic systems program. A two-level half-factorial experimental design approach is used.

The results from four experiments give an initial indication that the recirculation flow rate has little effect on Q_{net} and Q_s. Further experiments in the generic systems program are required to remove the confounding of recirculation flow rate with collector flow rate and collector area.

5. ACKNOWLEDGEMENT

The support of the U.S. Department of Energy through grant No. DE-FG03-86SF16036 is gratefully acknowledged.

6. NOMENCLATURE

C_p = specific heat, $W/m^2/C$
F_R = collector heat removal factor
I_T = total daily insolation, MJ/m^2
k = thermal conductivity, W/m/C
$K_{\tau\alpha}$ = empirical incident angle modifier
L = factor level, +1 or -1
m = mass flow rate, kg/s
M = design of experiments effect
Q_{aux} = daily energy input into auxiliary heater, kJ
Q_{cap} = energy capacity of the DHW system without solar, kJ
Q_{del} = daily energy delivered by DHW, kJ
Q_{dl} = desired daily load for DHW, kJ
Q_{lh} = daily energy input to collector loop heater, kJ
Q_{loss} = daily energy loss from auxiliary heater, kJ
Q_{net} = net daily energy delivered by solar, kJ
Q_{par} = daily energy consumed by parasitic devices, kJ
Q_{p1} = daily energy consumed by collector loop pump, kJ
Q_{p2} = daily energy consumed by recirculation loop pump, kJ
Q_{res} = energy remaining in solar storage tank at end of rating procedure, kJ
Q_s = daily energy delivered by solar, kJ
Q_u = daily energy delivered from collector array, kJ
R = average value of a response
SF = solar fraction
t = time, s
$T_{a,l}$ = average ambient temperature in the laboratory, C
T_i = temperature at location i, C
T_{main} = temperature of the water main, the cold water supply, C
T_{pre} = preheat temperature of the solar storage tank, C
T_{set} = temperature set point of the auxiliary water heater, C
U_L = collector heat loss coefficient, $W/m^2/C$
UA = Overall heat transfer coefficient, W/C
y = response
$\tau\alpha$ = transmissivity absorbtivity product for collector

7. REFERENCES

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8. APPENDIX

The SRCC energy quantities are defined by the following equations.

$$Q_{del} = \int_{t=0}^{t=t(Q_{del}=Q_{dl})} m_4\, C_p\, (T_{15} - T_{10})\, dt$$

$$Q_s = \int_{t=0}^{t=t(Q_{del}=Q_{dl})} m_3\, C_p\, (T_{12} - T_{10})\, dt$$

$$Q_{res} = \int_{t=0}^{t=t(T_{12} \leq T_{10}+3^\circ C)} m_3\, C_p\, (T_{12} - T_{10})\, dt$$

$$Q_{cap} = \int_{t=0}^{t=t(T_{15} \leq 35^\circ C)} m_4\, C_p\, (T_{15} - T_{10})\, dt$$

$$Q_{net} = Q_{del} - Q_{aux} + Q_{loss} - Q_{par}$$
$$= Q_s - Q_{par}$$

$$Q_{par} = Q_{p1} + Q_{p2}$$